
Your world in real time.
RTDS
Technologies
RTDS.COM

Frequency Scanning Approach for MMC Stability Analysis

RTDS Technologies Inc.
User's Groups Meeting
2019 China

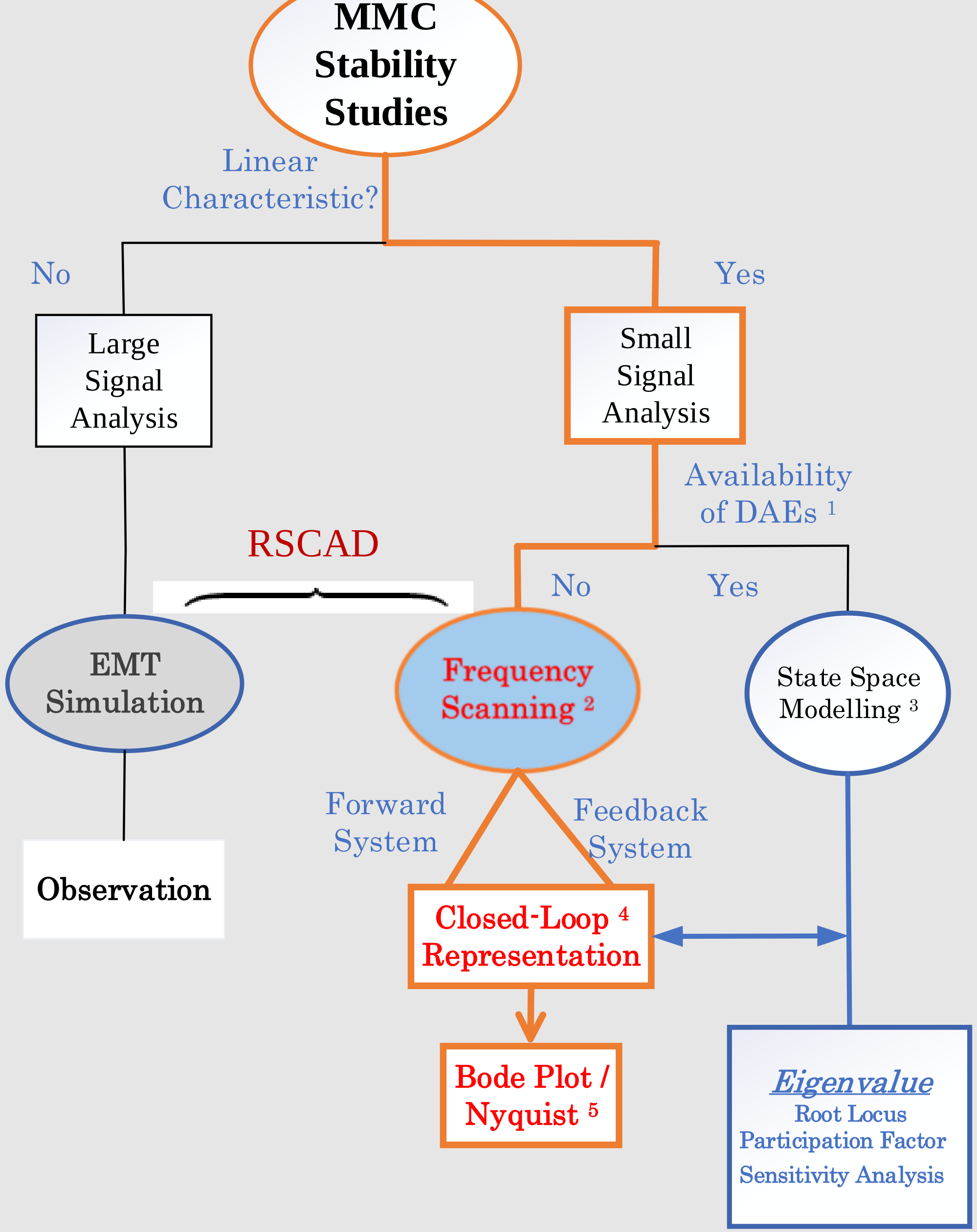
Outline

- Background and Theory
- AC-Converter interaction
- DC-Converter interaction
- System-Controller interaction
- Conclusions

Motivation - MMC Stability Studies

MMC-HVDC ac/dc interaction in wide band frequency range in several MMC projects:

- LuXi BTB-MMC-HVDC
- Xiamen MMC-HVDC
- YuE MMC-HVDC
- ZhangBei Multi-terminal MMC-HVDC
- KunLiuLong Multi-terminal Hybrid LCC-MMC-HVDC
- ZhangBei Renewable Energy Interconnection



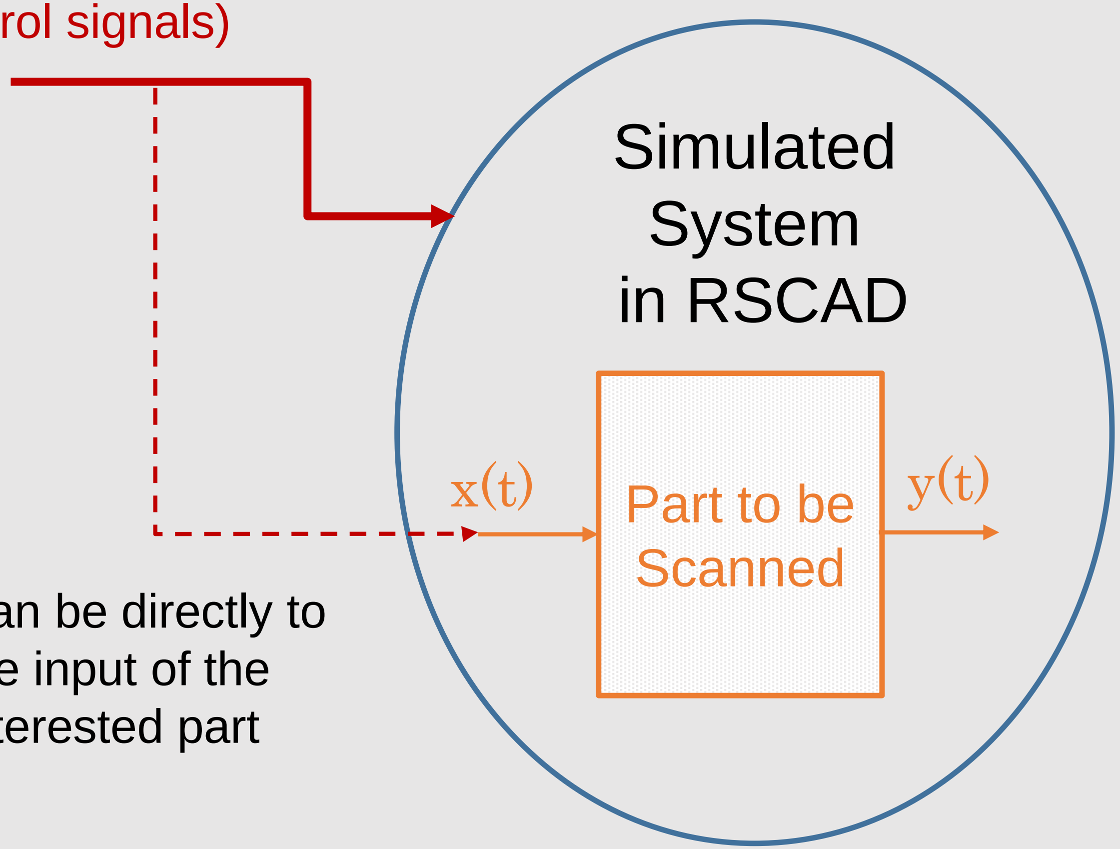
State Space Modelling Restrictions

- MMC Converter Modelling
- FD Transmission Lines
- Black Box Controller

Frequency Scanning

Apply a multi-sine [1] perturbation to the system (to voltage, current, or the control signals)

$$p(t) = \sum_{n=0}^{k} A \sin(2\pi f_n t + k {f_n}^2)$$



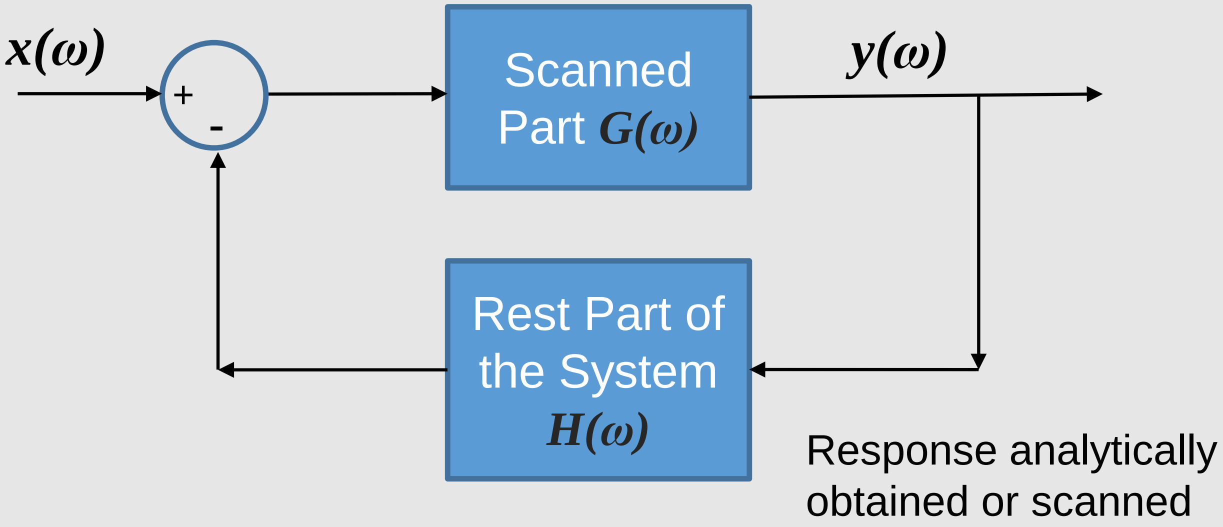
Can be directly to the input of the interested part

Apply DFT on x(t) and y(t) and calculate the response as a function of frequency.

- y(t), x(t) should include the same harmonic frequency (LTI system)

1. Conducted in EMT programs
2. Can only be conducted in Real-Time Simulators for black box hardware controller (Controller Hardware in-the-loop: CHIL)

1 Xiao Jiang and A. M. Gole, "A frequency scanning method for the identification of harmonic instabilities in HVDC systems," in *IEEE Transactions on Power Delivery*, vol. 10, no. 4, pp. 1875-1881, Oct. 1995.



Closed-loop transfer function

$$\frac{y(\omega)}{x(\omega)} = \frac{G(\omega)}{I + G(\omega) * H(\omega)}$$

Open-loop transfer function

$$Tf(\omega) = G(\omega) * H(\omega)$$

Stability Determination

Tf Poles ⟷ SS Eigenvalue

At frequency ω_1, the close loop poles $\lambda c(\omega_1)$:

- SISO: complex number
- MIMO: eigenvalue [1]

At frequency ω_1, open loop eigenvalue $\lambda(\omega_1)$

Stability Boundary

$Mag\ [\lambda(\omega_1)] = 1\ \ \&\&\ Phase[\lambda(\omega_1)] = 180\text{Deg}$

$Mag[\lambda(\omega_1)] = 1$ → *Phase Margin*

$Phase[\lambda(\omega_1)] = 180\text{Deg}$ → *Magnitude Margin*

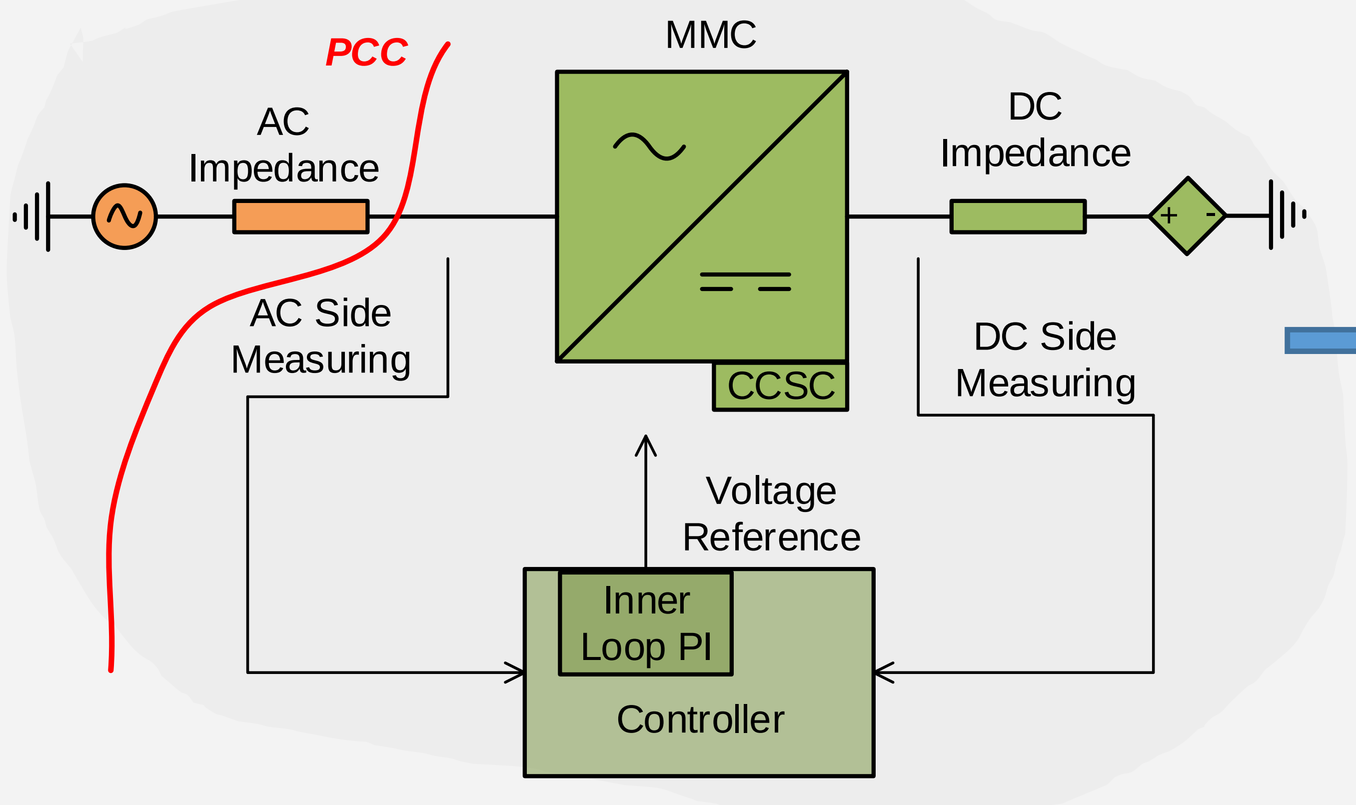
1 G. J. MAcFARLANE & I. POSTLETHWAITE (1977) The generalized Nyquist stability criterion and multivariable root loci, International Journal of Control, 25:1, 81-127, DOI: 10.1080/00207177708922217

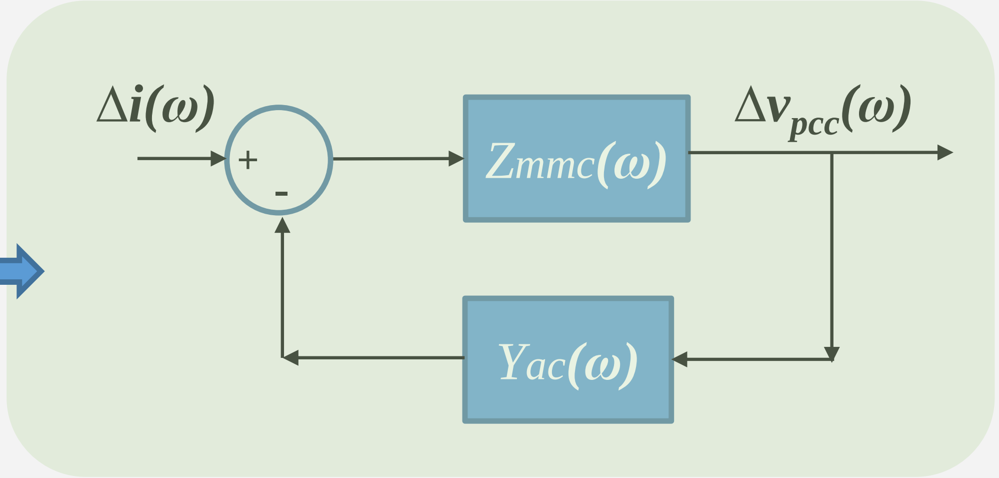
Outline

- Background and Theory
- AC-Converter interaction
- DC-Converter interaction
- System-Controller interaction
- Conclusions

Closed-loop Representation

For AC-Converter interaction

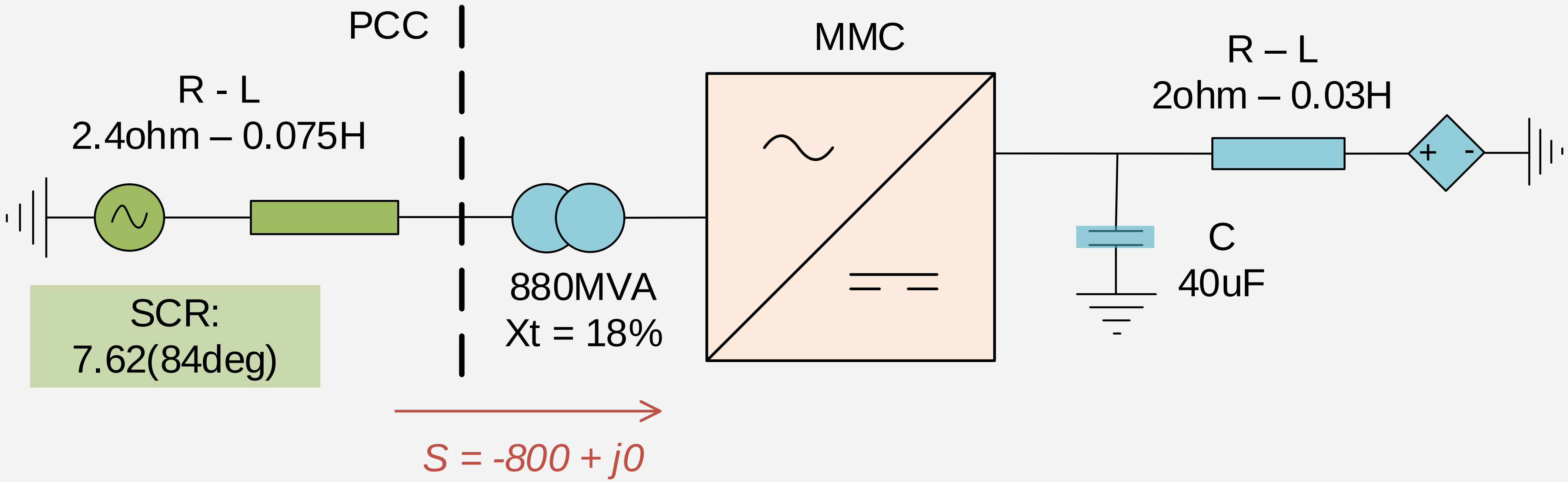




The AC system and rest part are inter-connected as a closed-loop system at: **the PCC bus**

Application Example

CIGRE DCS1 one Terminal System



Single end MMC (based on the CIGRE DCS1 system), control system not plotted here

Decoupled controller controls ac active power (-800MW) and reactive power (0Mvar)

AC impedance analytically obtained and converter side impedance scanned (in the dq0 domain)

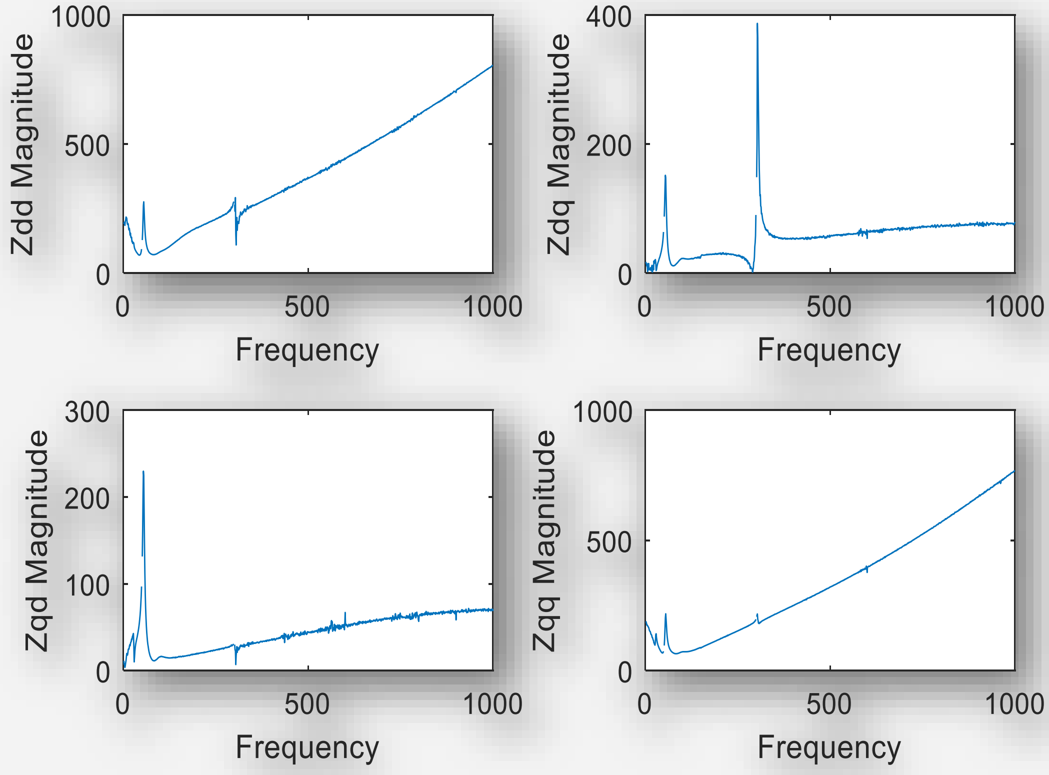
Converter Side Frequency Scanning

- Looking from PCC, the system is time-invariant when represented in the dq0 domain (small disturbance)
- Strong coupling between D and Q axis; no coupling between DQ and 0 axis; zero sequence does not flow into the dc side
- The converter side impedance has the format of (also the ac side should be in the same format):

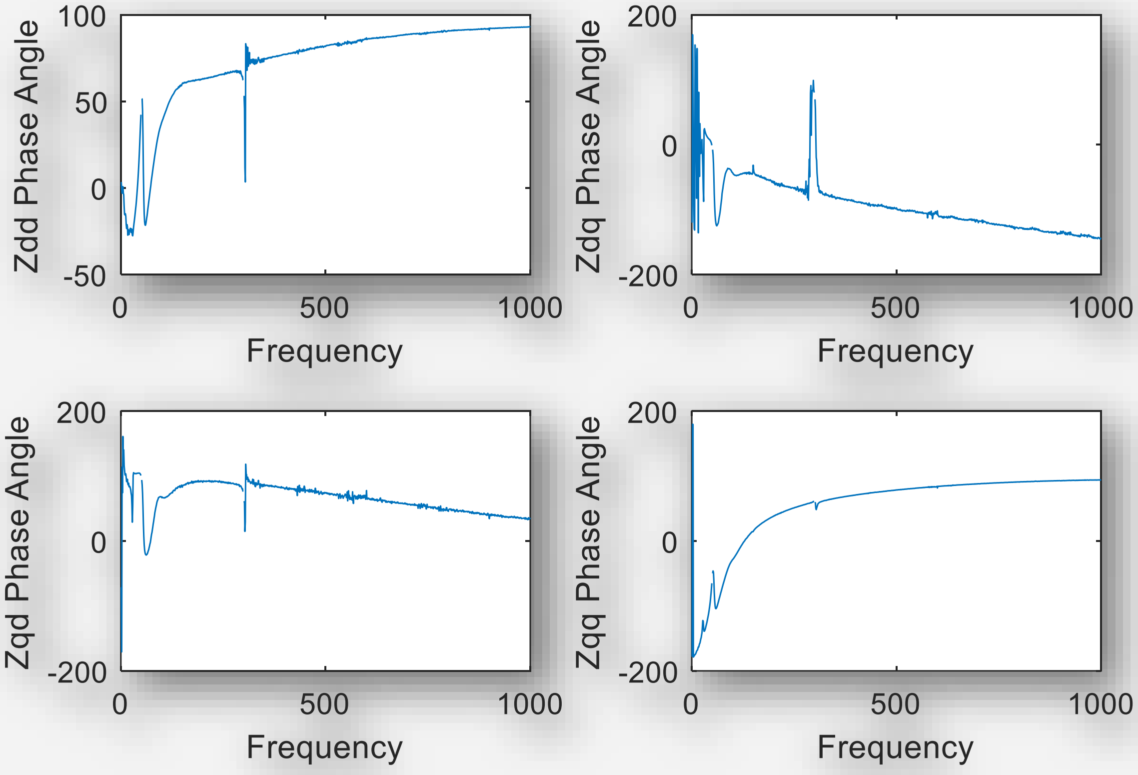
$$Z_{dq0} = \begin{bmatrix} Z_{dd} & Z_{dq} & 0 \\ Z_{qd} & Z_{qq} & 0 \\ 0 & 0 & Z_{00} \end{bmatrix}$$

Converter Side Impedance

Looking from the PCC bus



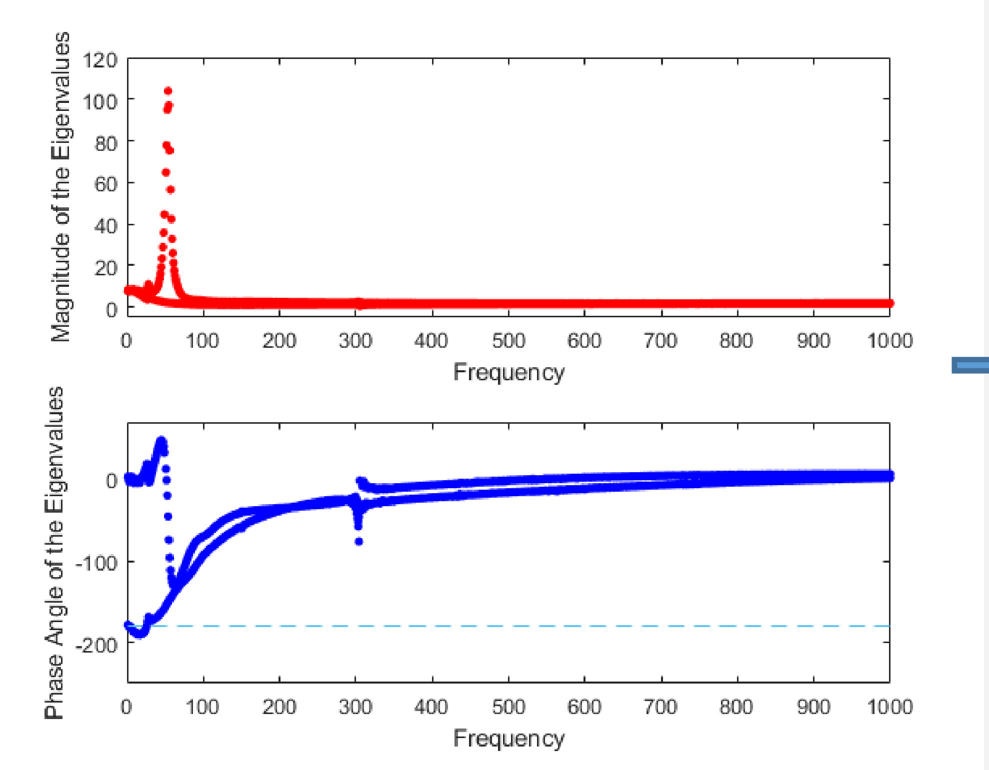
Magnitude

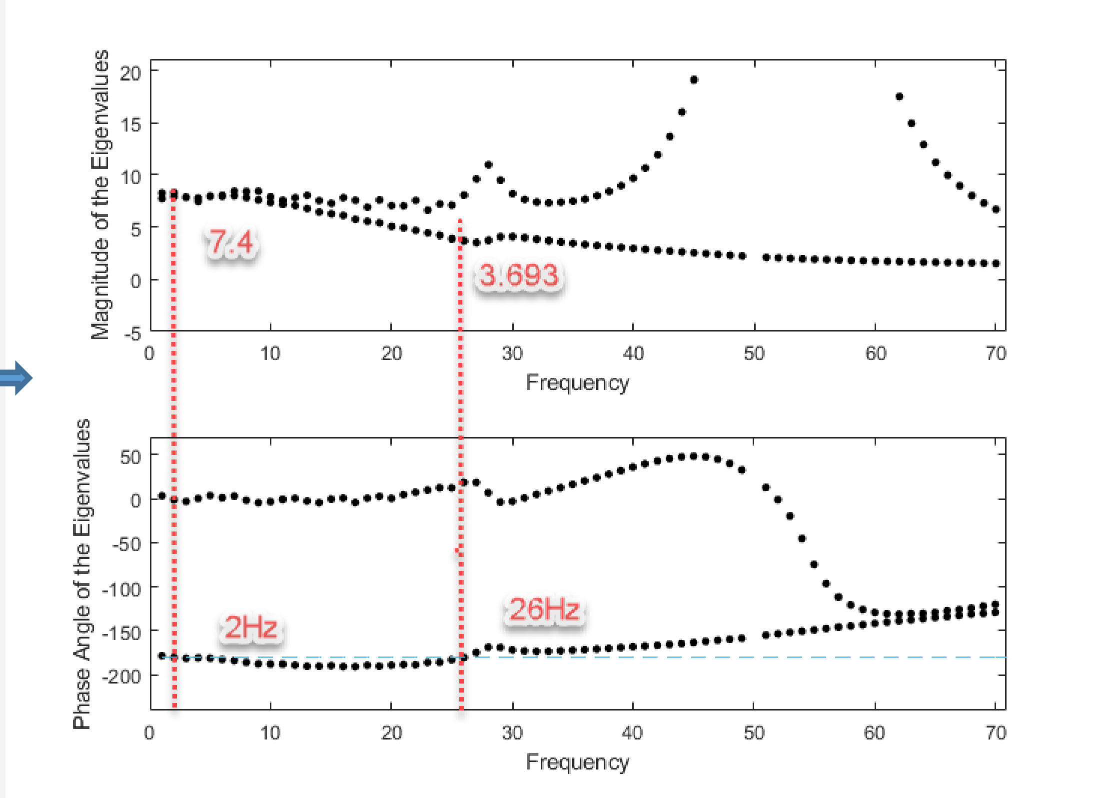


Phase Angle

Bode Plot of the Eigenvalues

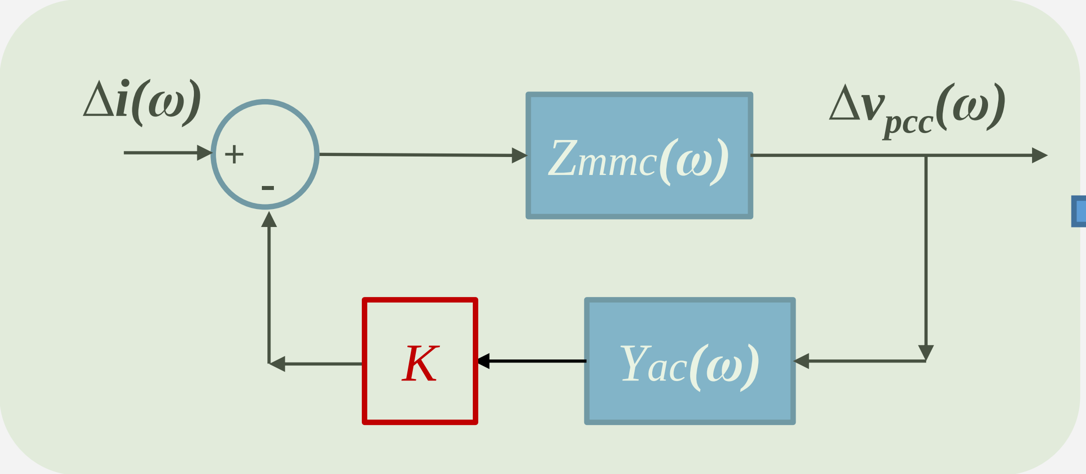
Of the Loop Gain Matrix $Z_{mmc}(\omega)Y_{ac}(\omega)$





The magnitude margin – $M(\omega_1)$: @26 Hz is 3.693; @2 Hz is 7.4

Result Validation

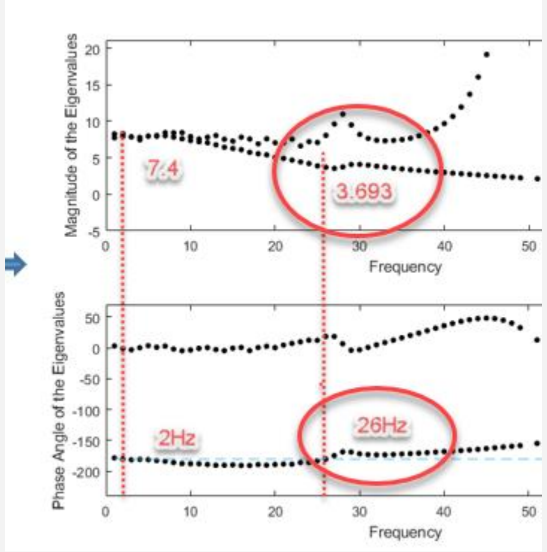


In previous closed-loop (no K):

$$\lambda(\omega_1) = eig[Z_{mmc}(\omega_1) * Y_{ac}(\omega_1)]$$

In the above closed-loop:

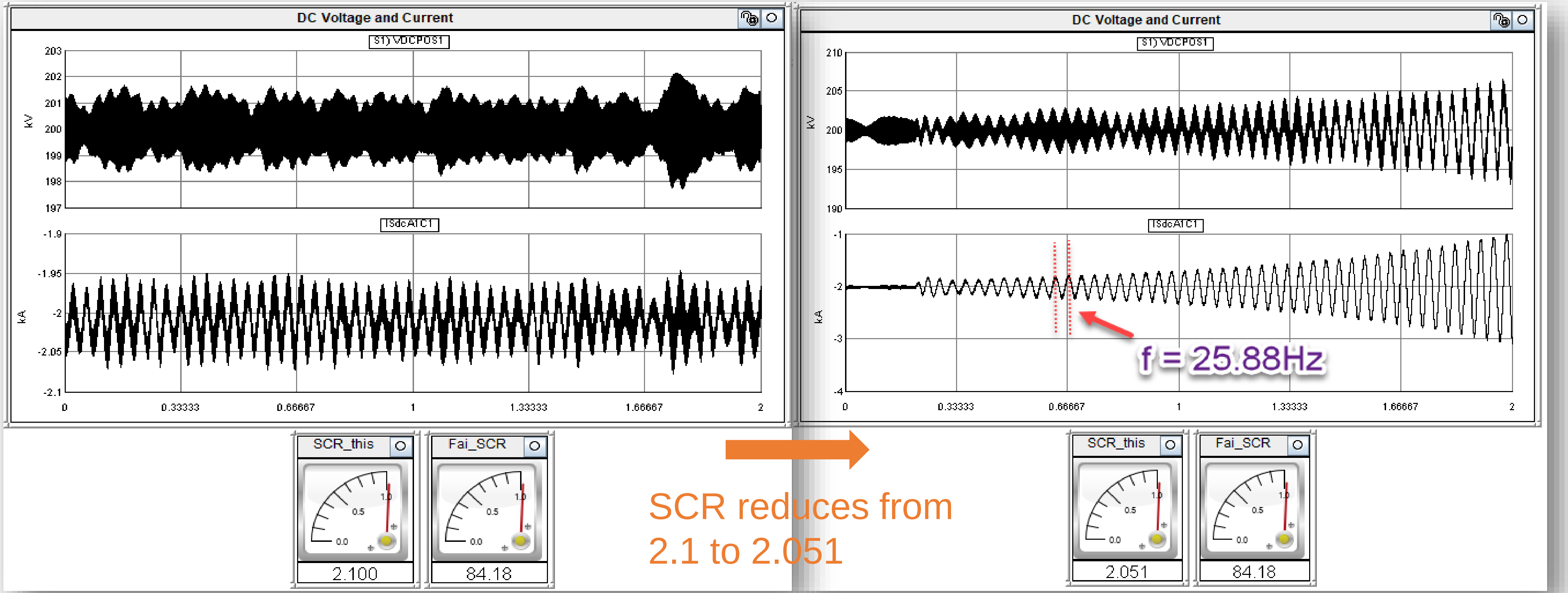
$$K\lambda(\omega_1) = eig[Z_{mmc}(\omega_1) * KY_{ac}(\omega_1)]$$



If the SCR of the AC system, i.e., Y_{ac} is reduced by 3.693, the new eigenvalue would be -1 at 26Hz.

The system would be marginally stable
(Critical SCR = 7.62/3.693 = 2.063).

Result Validation



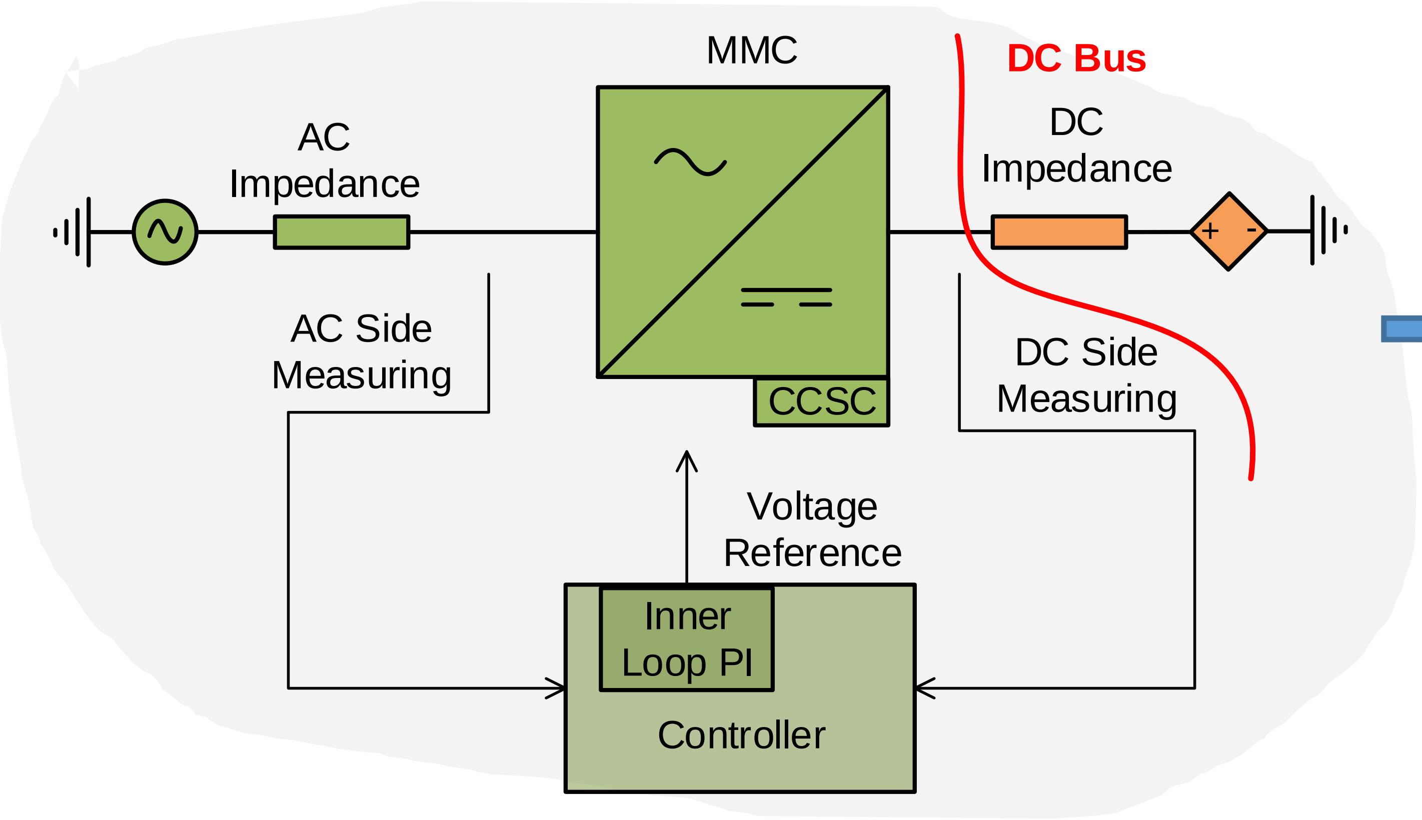
- The critical SCR is between 2.051 to 2.1 (2.063 from Bode Plot)
- The oscillation frequency at critical SCR is 25.88Hz (26Hz from Bode Plot)

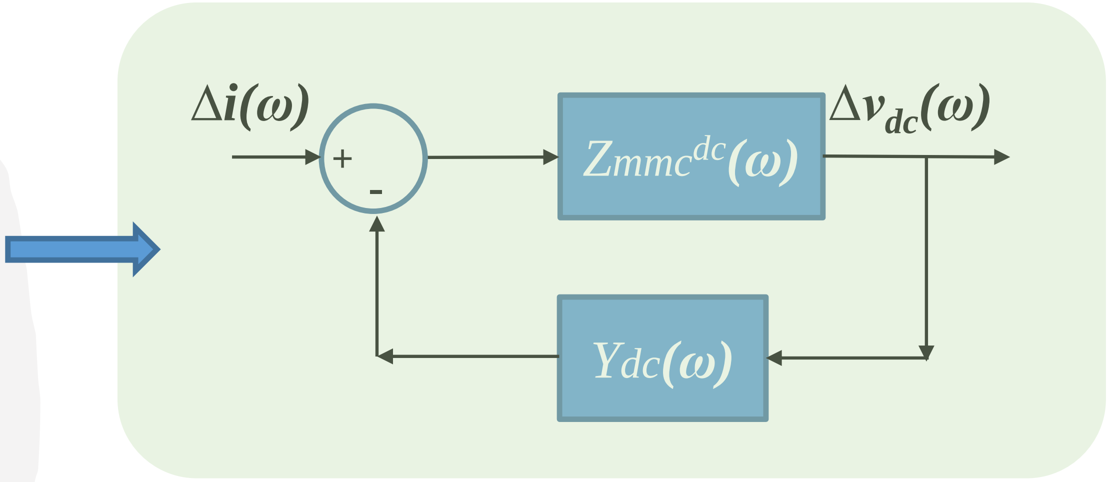
Outline

- Background and Theory
- AC-Converter interaction
- DC-Converter interaction
- System-Controller interaction
- Conclusions

Closed-loop Representation

For DC-Converter interaction

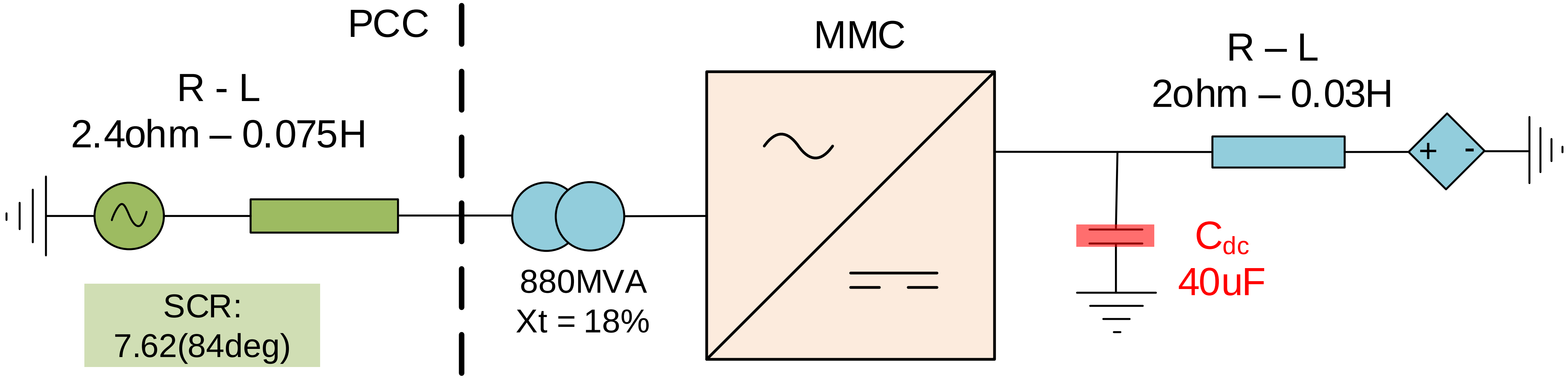




The DC system and rest part are inter-connected as a closed-loop system at: **the DC bus**

Application Example

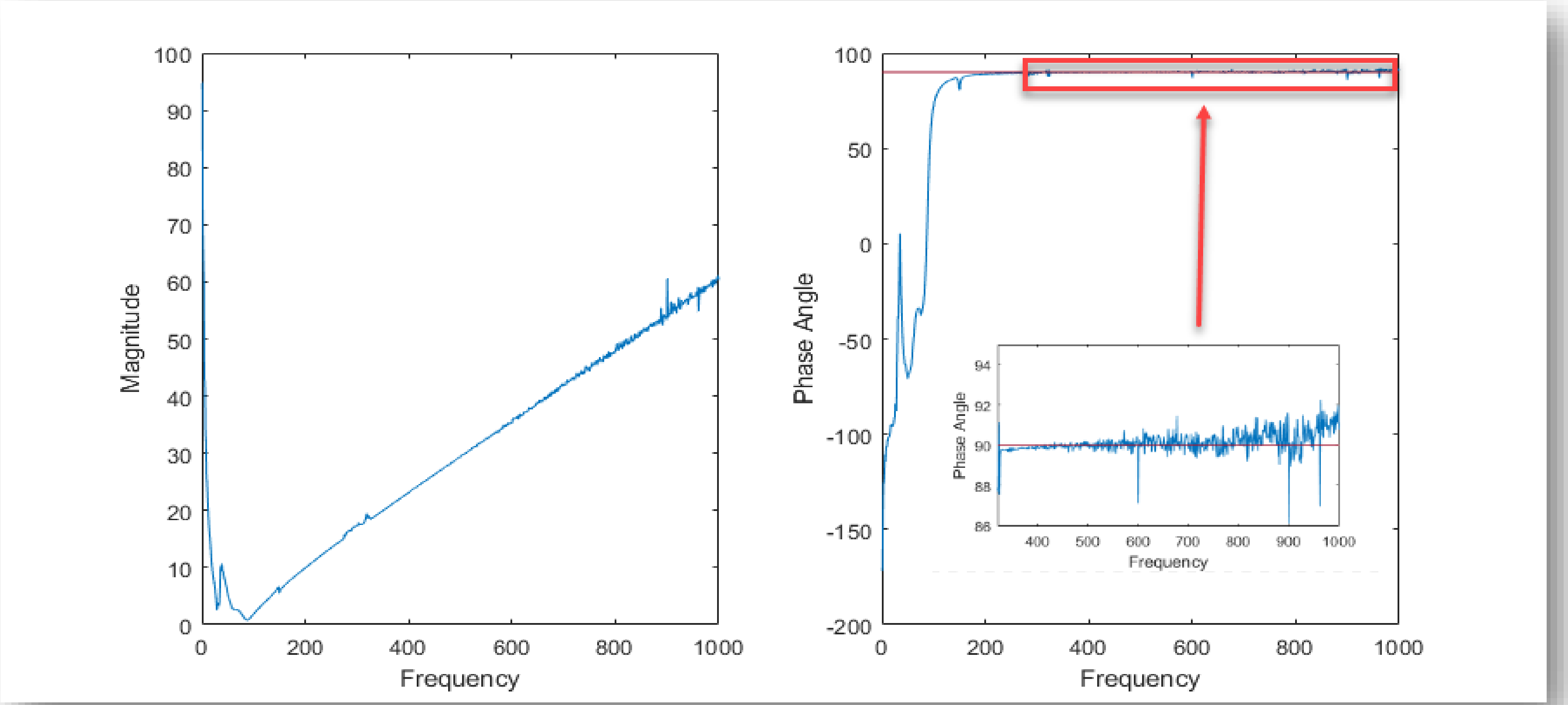
CIGRE DCS1 one Terminal System



- Same configuration as previous example, control system not plotted here
- DC side impedance obtained analytically
- Converter side impedance obtained from scanning

Converter Side Impedance

Looking from the DC bus



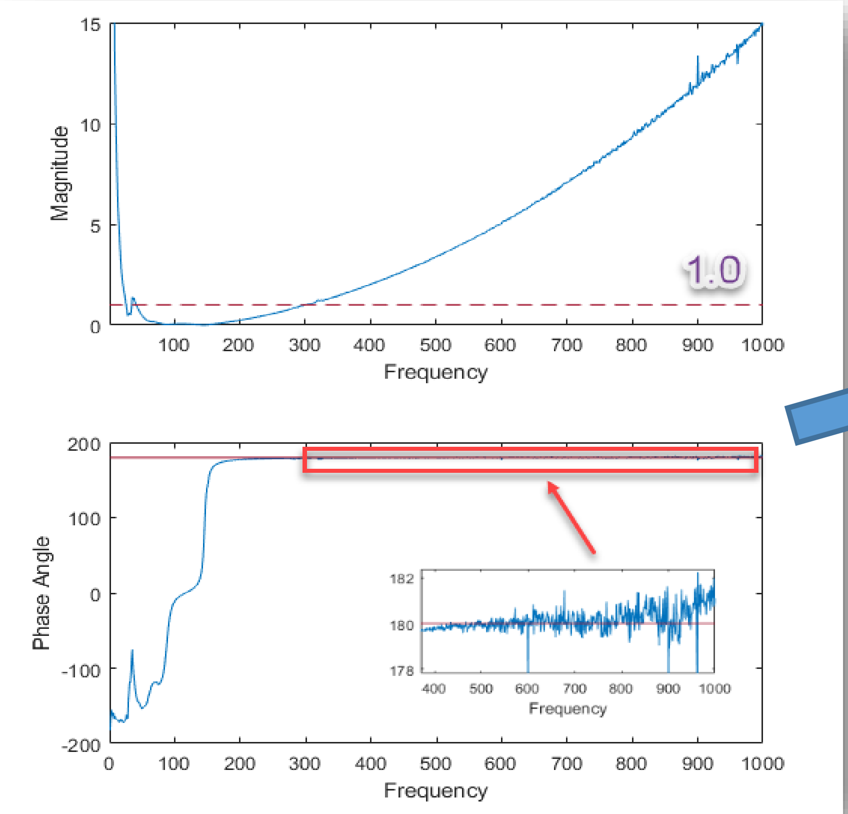
Magnitude

Phase Angle

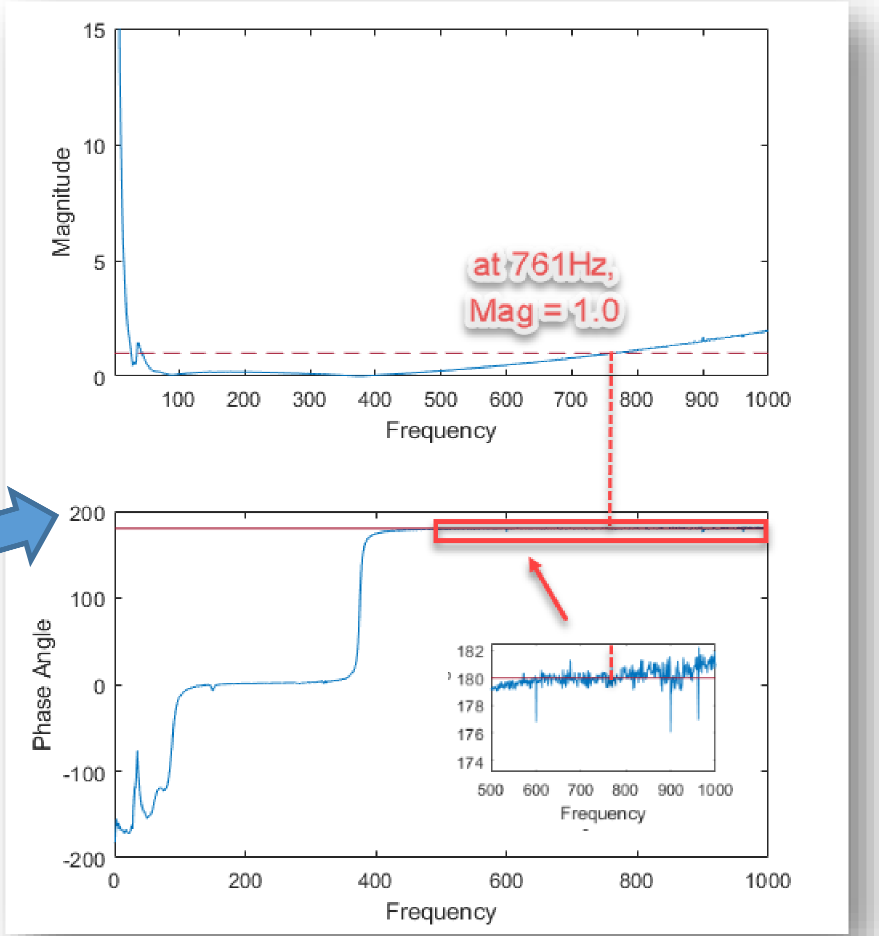
Weak damping in high frequency

Bode Plot

Of the Loop Gain $Z_{mmc}^{dc}(\omega)Y_{dc}(\omega)$



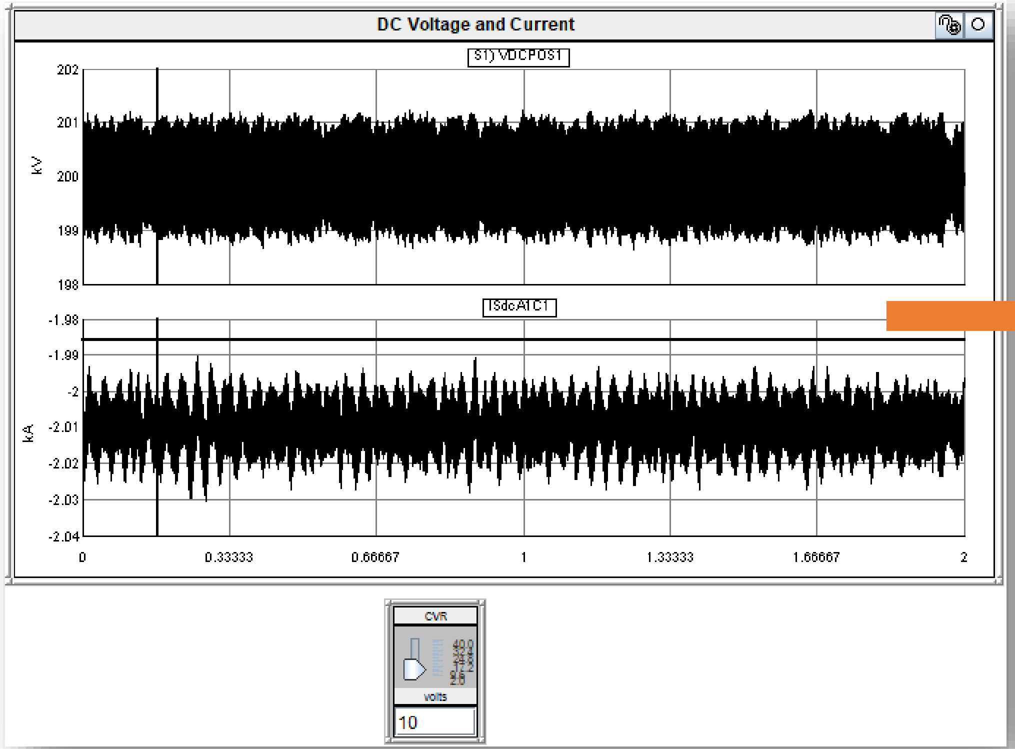
Reduce C_{dc}



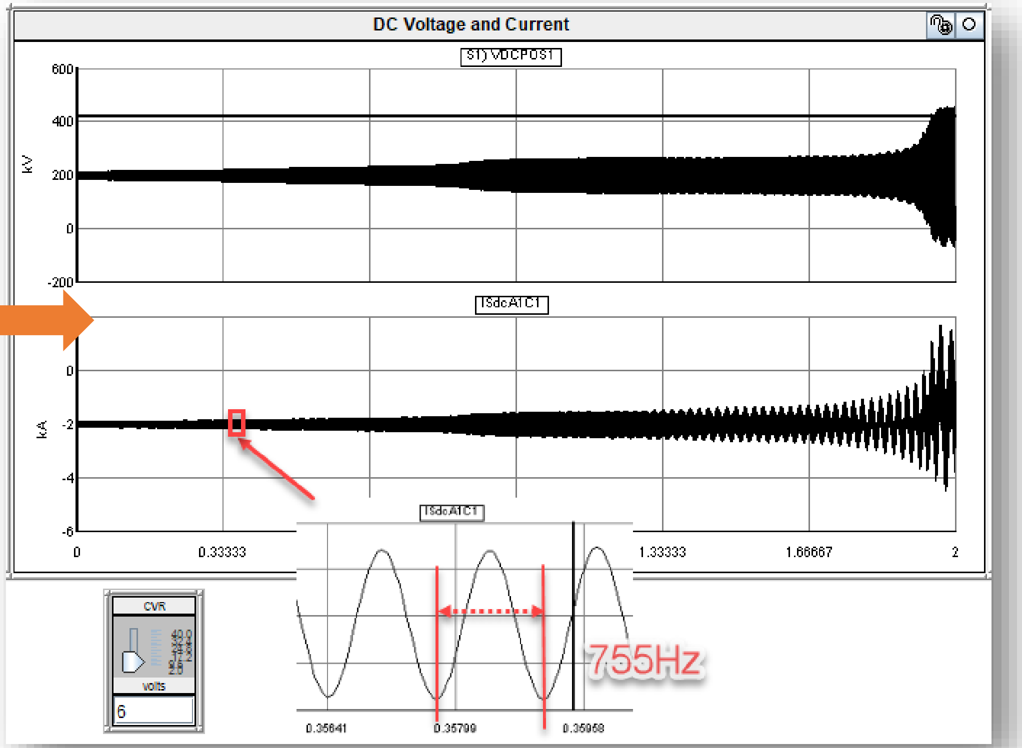
C_{dc} = 40uF, the system is stable, Margin > 1

C_{dc} = 6uF, at 761Hz, the magnitude is 1.0 and phase angle -180deg

Result Validation



Reduce C_{dc} from *10uF* to *6uF*



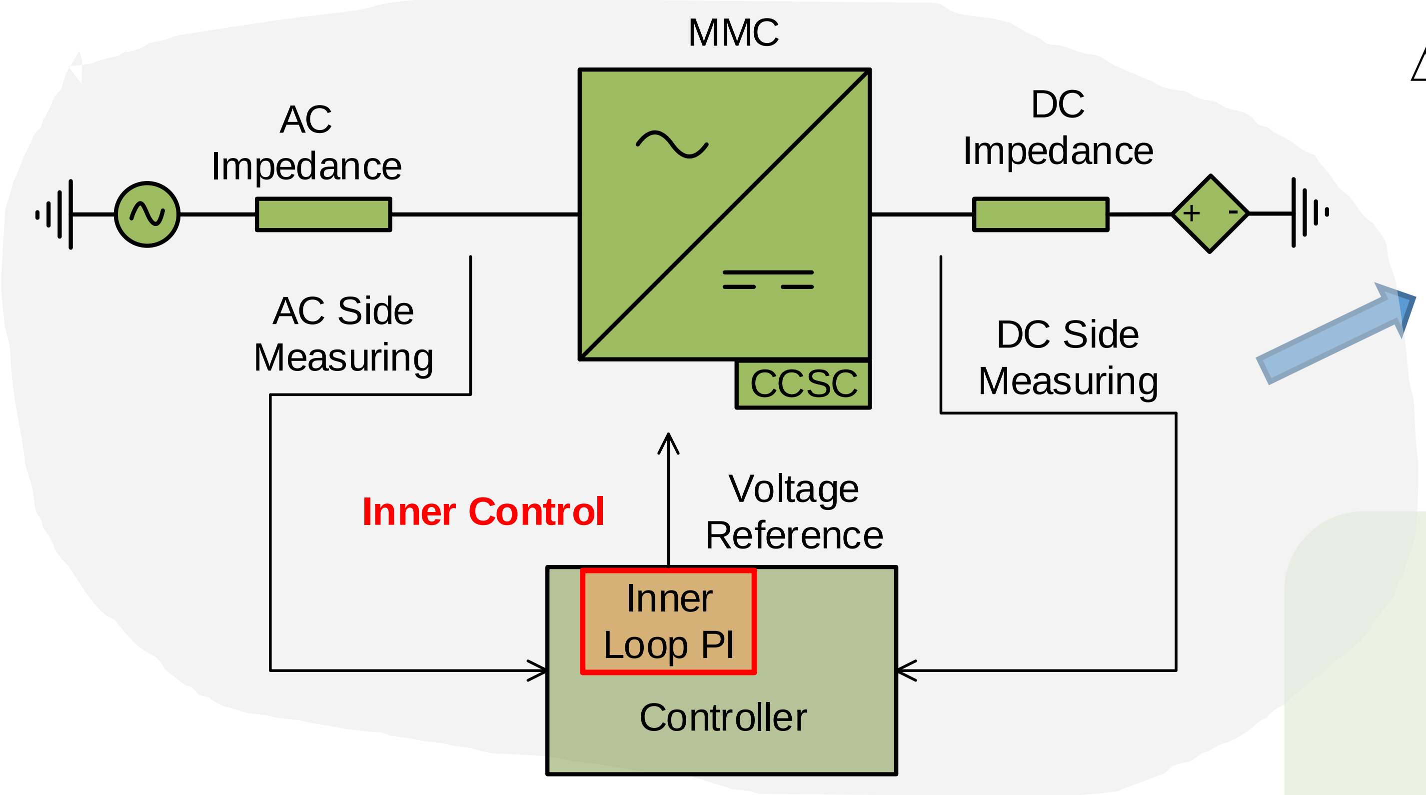
- The critical value of is C_{dc} between 6uF to 10uF (6uF from Bode Plot)
- The oscillation frequency at critical C_{dc} is 755Hz (761Hz from Bode Plot)

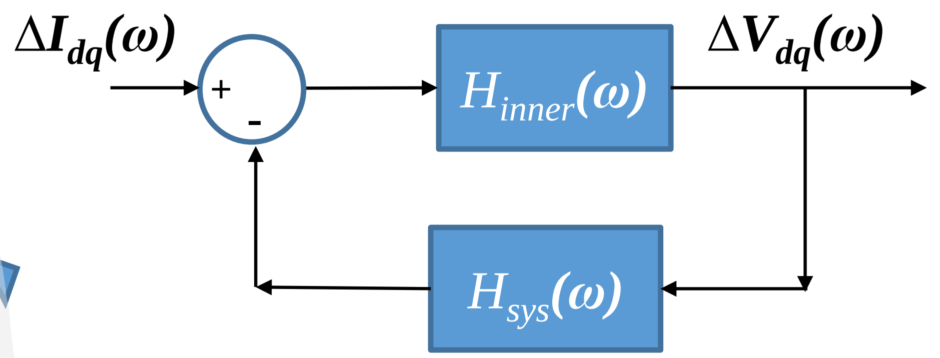
Outline

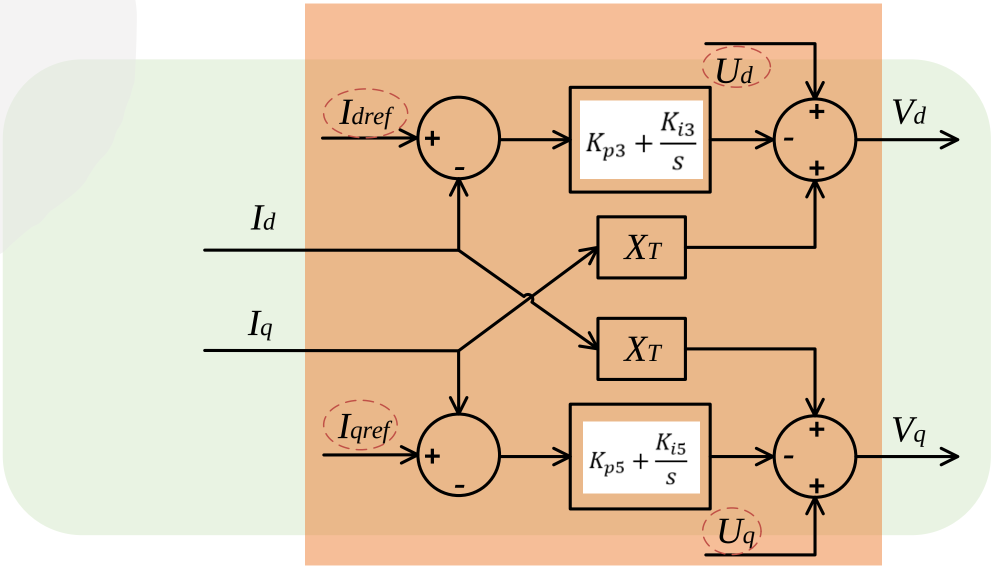
- Background and Theory
- AC-Converter interaction
- DC-Converter interaction
- System-Controller interaction
- Conclusions

Closed-loop Representation

For System-Controller interaction



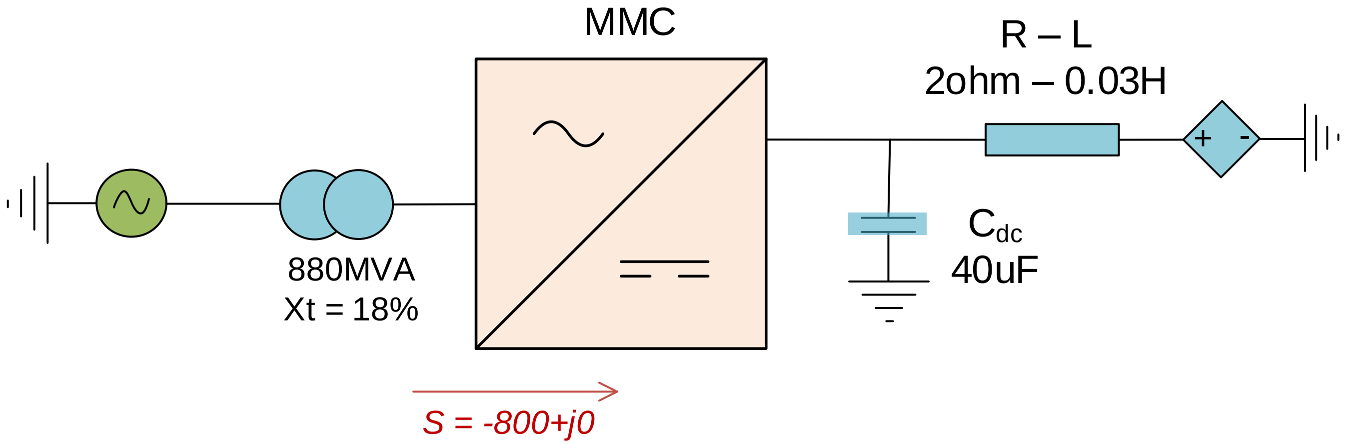


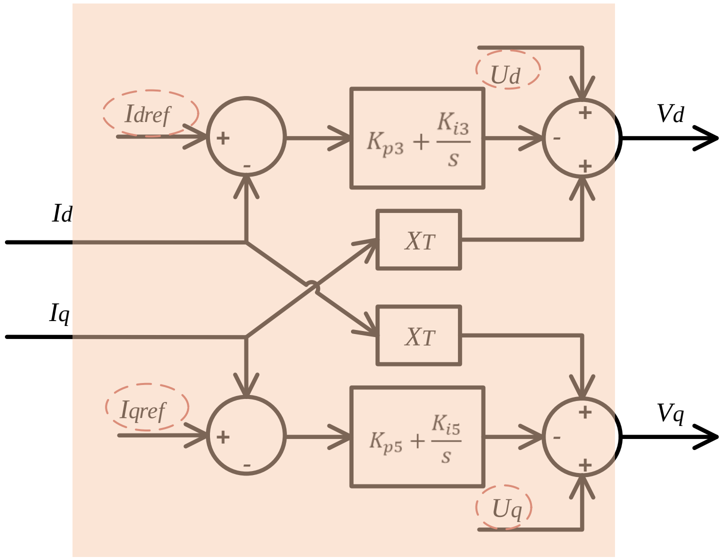


The inner loop controller and the rest part are inter-connected as a closed-loop system at the **Inner Control Boundary**

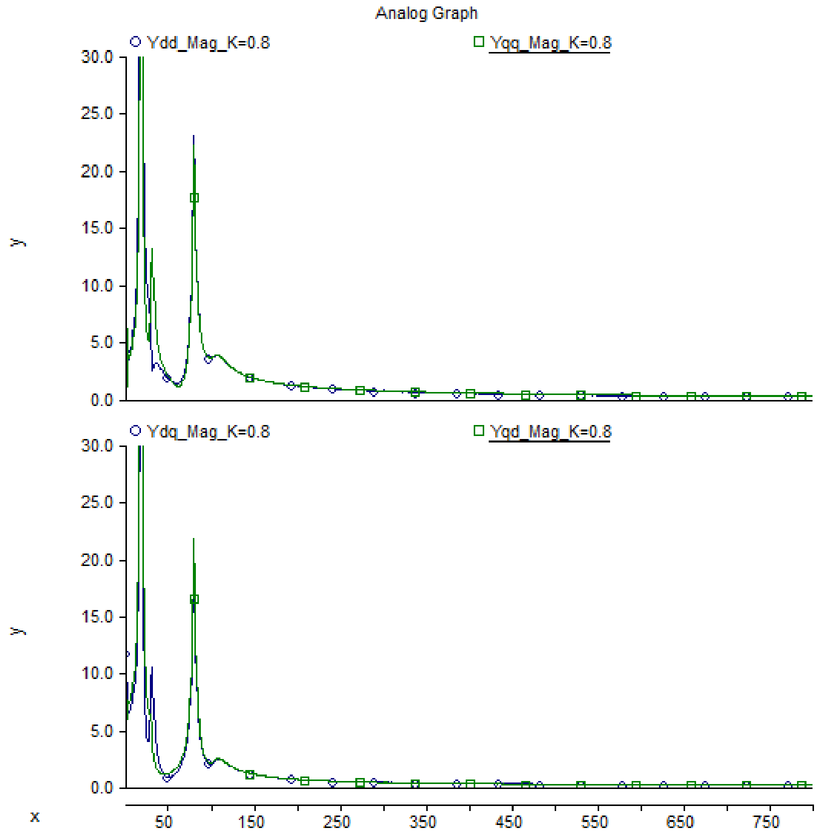
Application Example

CIGRE DCS1 one Terminal System

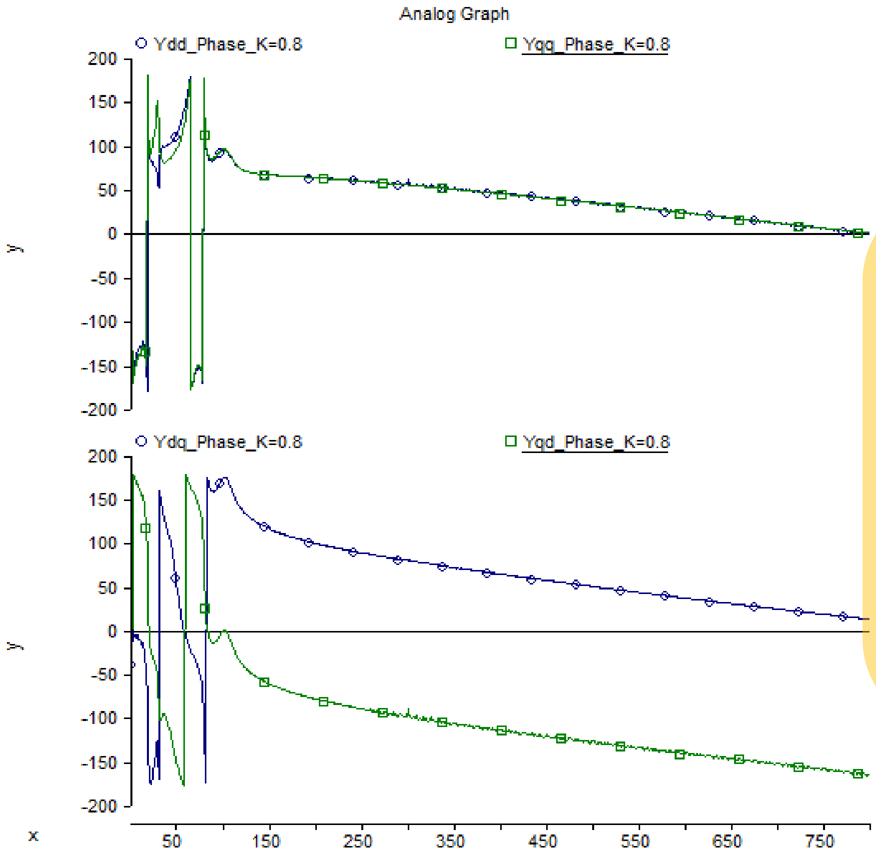




System Response H_{sys}



Magnitude

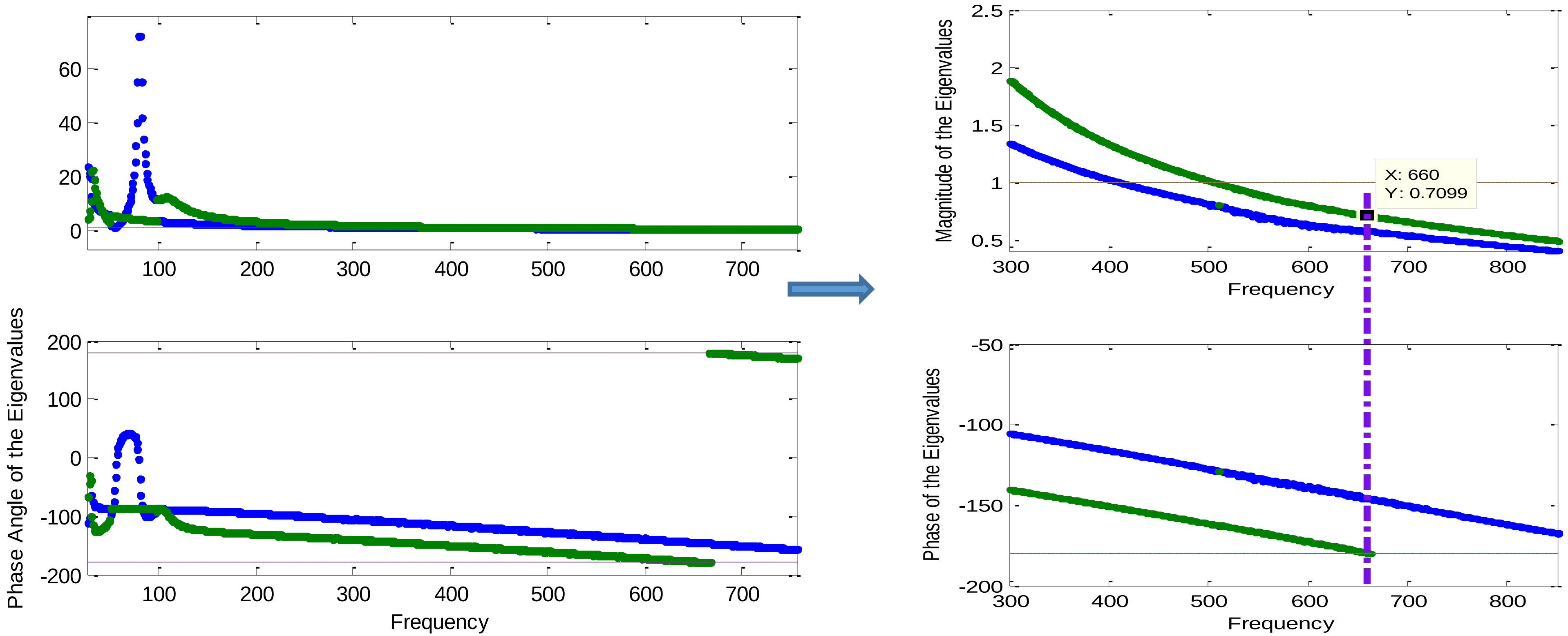


Phase Angle

- Input: Vd/Vq
- Output: Id/Iq
- The response of the inner loop can be obtained analytically

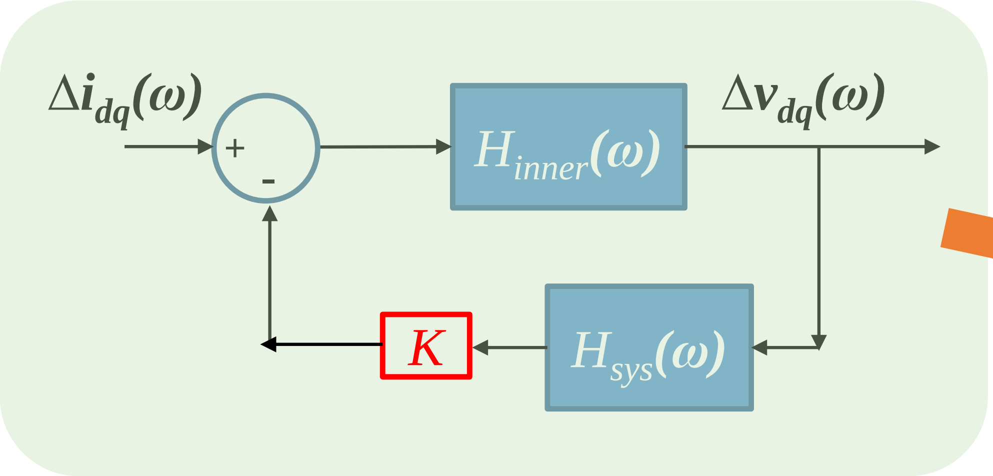
Bode Plot of the Eigenvalues

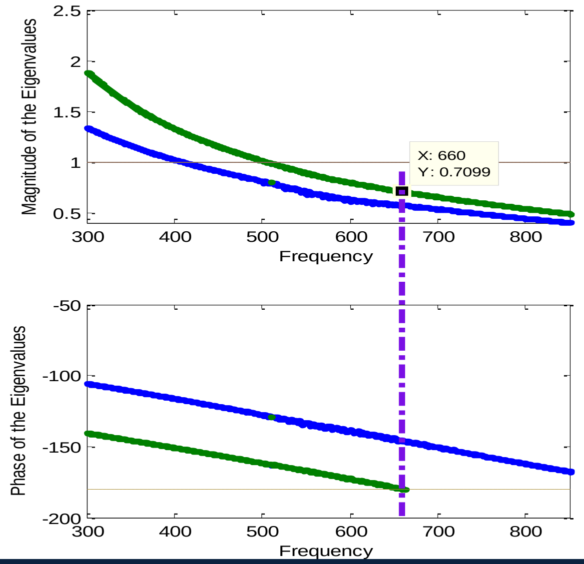
Of the Loop Gain Matrix $H_{inner}(\omega)H_{sys}(\omega)$



The magnitude margin – $M(\omega_1)$: @660 Hz is 1/0.7099=1.408

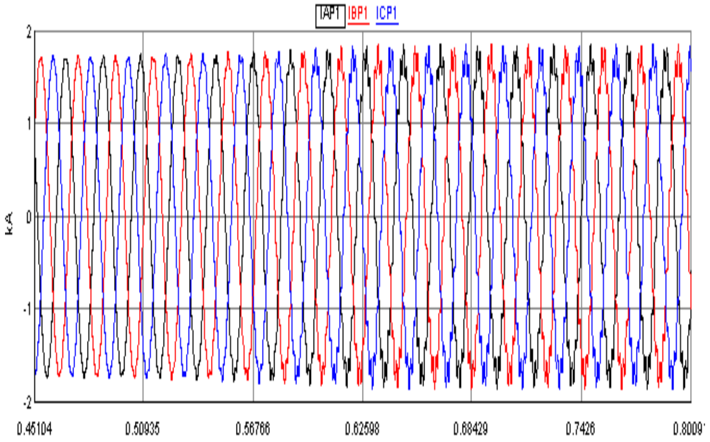
Result Validation

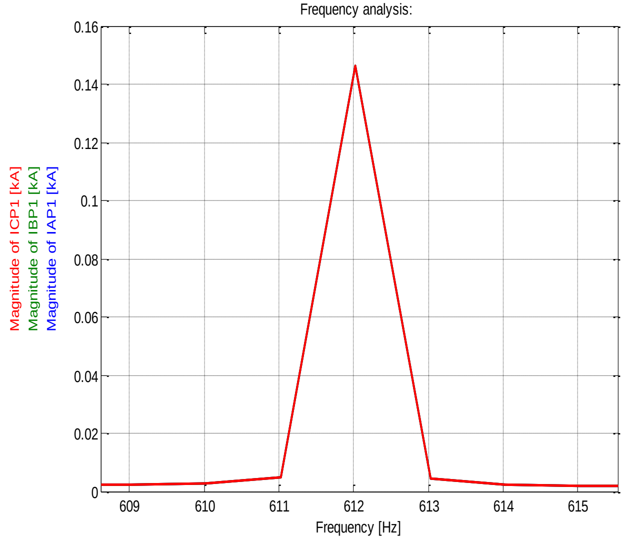


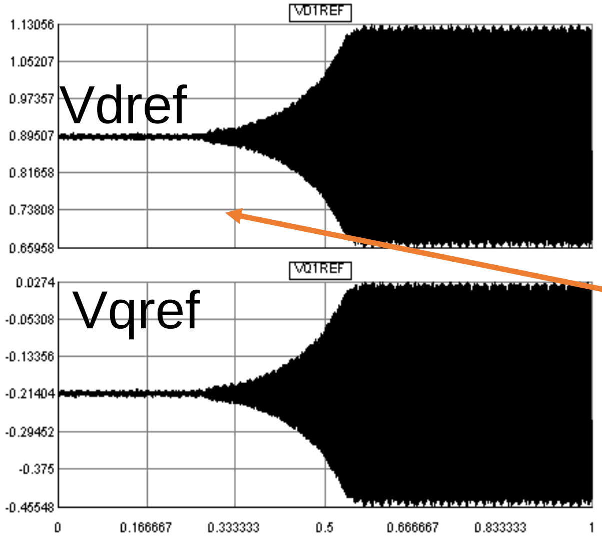


- Increasing the value of K, i.e., the gain of the inner loop by 1/0.7099=1.408 gives a marginally stable system
- The oscillation frequency with the above K value, i.e., 1.408 would be 660Hz

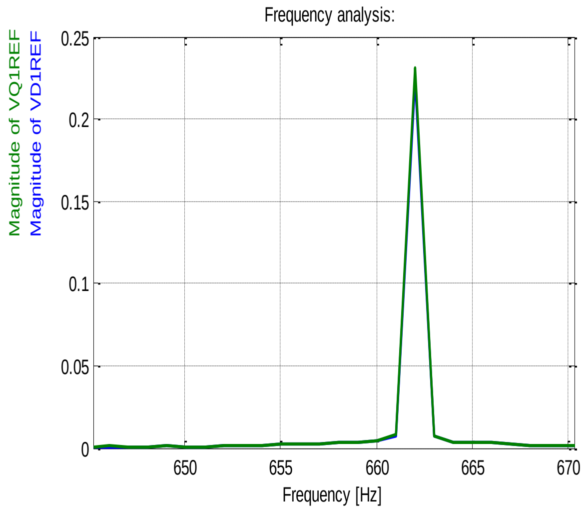
Result Validation





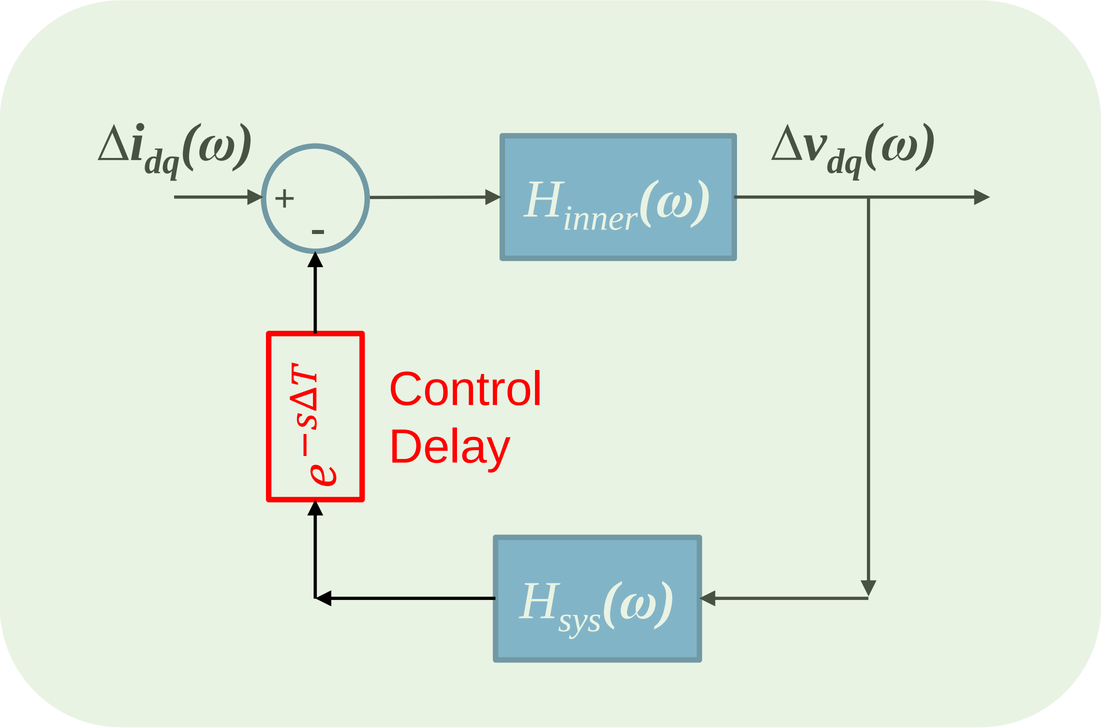


Step change of K from 1.39 to 1.41



- The oscillation frequency at critical K value is 612Hz in phase domain
- The oscillation frequency at critical K value is 612Hz in dq domain (660Hz from Bode Plot)

Influence of the Control Cycle



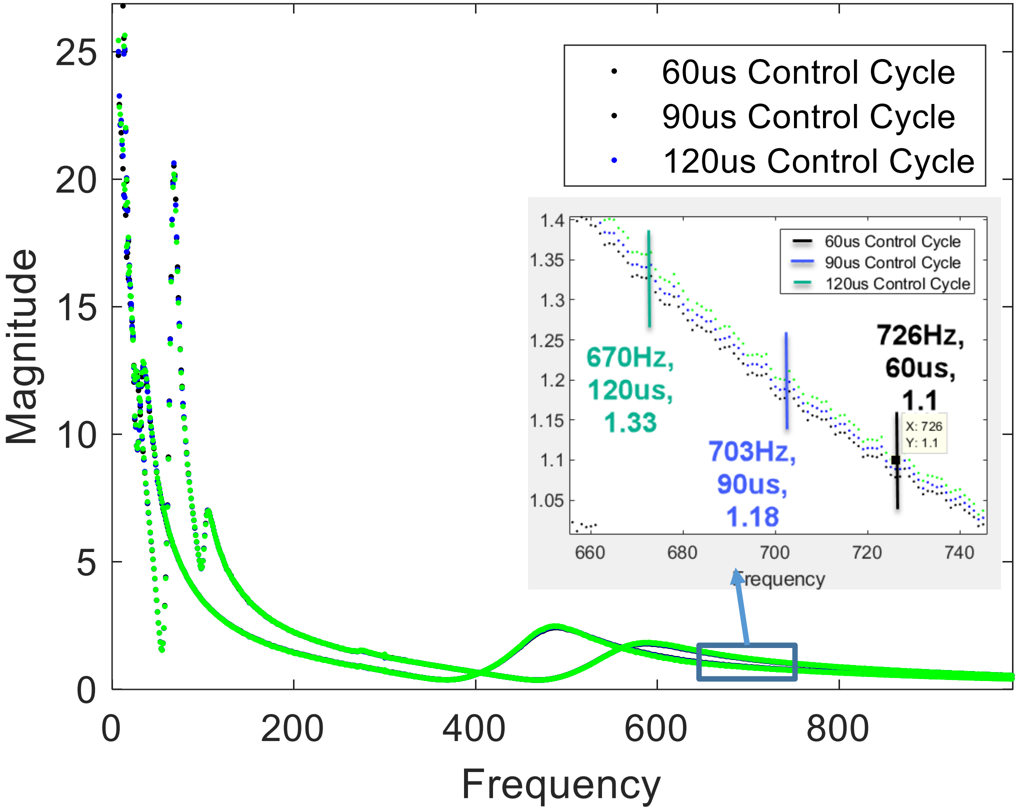
Real Word Controller-in-Loop

- At low frequency, the control delay applies a small phase shift to the loop gain
- At high frequency, the control delay applies a large phase shift, e.g., *f = 600Hz, ∆T = 50us*, the phase shift of the delay:

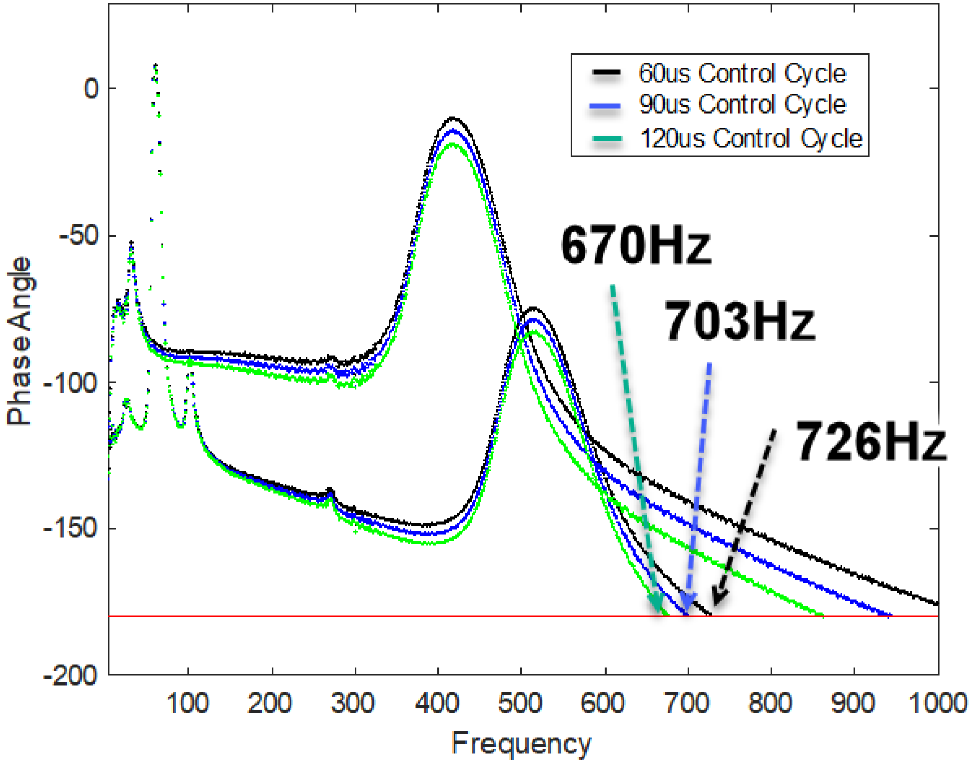
$$\phi = \frac{360deg}{cycle} * 600Hz * 50us = 10.8deg$$

- The crossing frequency of 180deg on the Bode Plot can be changed

Bode Plot of Different Control Cycles



Magnitude, all three control cycle give the same result



Phase Angle, delay shown as phase shift (proportional to frequency)

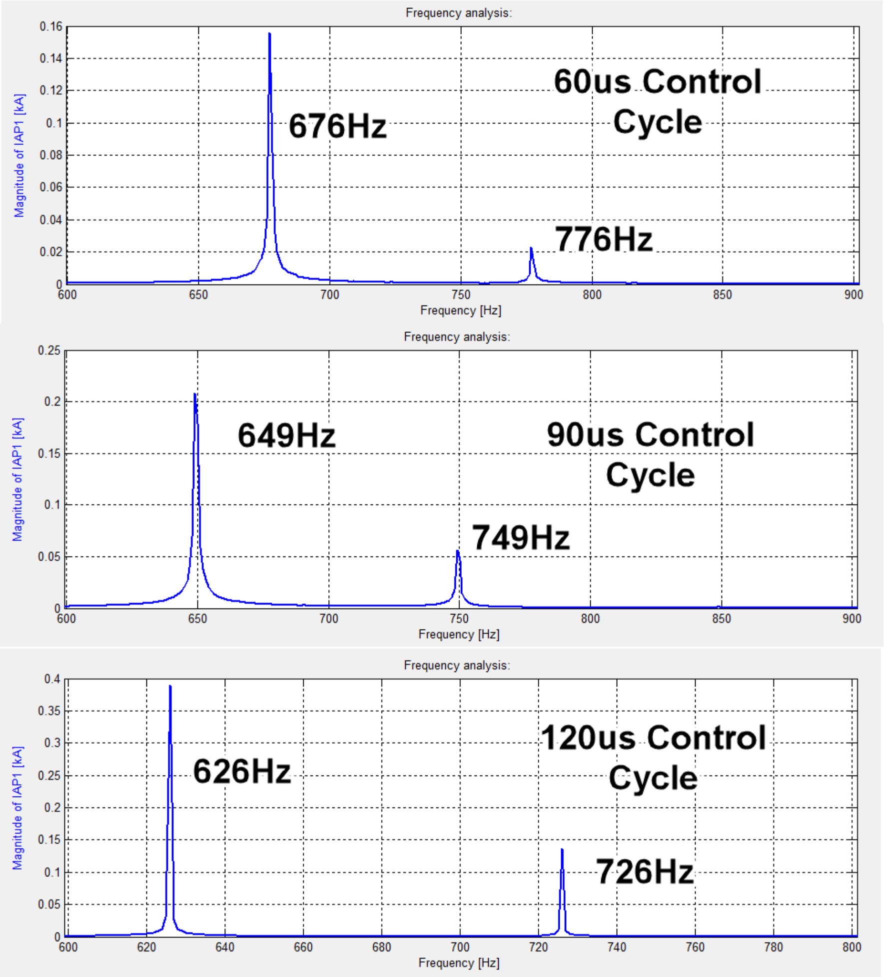
Oscillation Frequency in Simulation

FFT on Phase A current

- 60us Control Cycle: 726Hz in the dq0 domain
- Bode Plot: 726Hz

- 90us Control Cycle: 699Hz in the dq0 domain
- Bode Plot: 703Hz

- 120us Control Cycle: 676Hz in the dq0 domain
- Bode Plot: 670Hz



Outline

- Background and Theory
- AC-Converter interaction
- DC-Converter interaction
- System-Controller interaction
- Conclusions

Conclusions

- The closed-loop representation of MMC based system can be very flexible, i.e., different interface boundaries can be chosen, to study the influence of a specified part of the system on the system stability.
- The frequency scanning component in RSCAD can accurately extract the frequency dependent response of the interested part of the system.
- The application of Bode Plot on the responses closed-loop system gives accurate result of the system stability and oscillation information.

Conclusions

- AC-Converter (and its control) involves sub-synchronous frequency oscillation and the *SCR* plays an important role.
- The MMC impedance response looking from DC side has very weak damping (even negative) in high frequency range, i.e., >500Hz.
- A high inner loop gain of the decoupled controller can easily excite high frequency oscillation regardless of the ac system and outer loop control configuration.
- The oscillation frequency (at high frequency range) as well as the system stability are also influenced by the control cycle, i.e., the time delay between the controller and the electrical system.

THANK YOU!
QUESTIONS?

RTDS Technologies